

DESIGN AND TESTING OF A WEED CONTROL SYSTEM FOR SOYBEAN INTER-ROW WEEDING MACHINES IN DUAL-SPEED MODE

双测速模式下的大豆行间除草机控制系统设计与试验

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ABSTRACT

To solve the problems of straw accumulation and crop injury caused by the inability of the straw-raking motor on a designed soybean inter-row weeder to adjust its operating speed in real time according to the machine's forward speed, a variable-speed operation method based on dual-speed measurement using GNSS positioning and an encoder is proposed. By setting operational parameters such as working mode and straw density, the system dynamically adjusts the rotational speed of the straw-raking motor in real time based on GNSS and encoder data, ensuring synchronization with the implement's forward speed. Field performance tests were conducted at three working speeds (3, 5, and 7 km·h⁻¹), with and without the straw-raking control system as experimental controls. The results show that at 7 km·h⁻¹, the average weed removal rate increased by 2.52%, the average straw coverage rate increased by 4.95%, and the average seedling damage rate decreased by 2.28%. These findings provide practical technical references for the implementation of mechanical weed control systems.

摘要

针对所设计大豆行间除草机的拨秸转速不能随机具前进速度调整作业转速容易导致秸秆堆积压苗的问题, 提出了一种基于 GNSS 定点与编码器双测速的变速作业方法。通过设置作业模式与秸秆密度等作业参数, 根据 GNSS 与编码器的测速信息实时调节拨秸电机的作业转速, 从而实现与机具前进速度的匹配。以有无拨秸控制系统为对照, 进行了 3 种作业速度 (3、5、7 km·h⁻¹) 下的田间性能试验。试验结果表明: 当作业速度为 7 km·h⁻¹ 时, 平均除草率和平均秸秆覆盖率分别提高了 2.52% 和 4.95%, 平均伤苗率降低了 2.28%, 为机械除草控制系统的应用提供了实用技术参考。

INTRODUCTION

Weed infestation in fields is a key factor affecting soybean yield. Currently, research on mechanical weed control in complex field environments has been conducted, incorporating intelligent technologies such as multi-source real-time sensing and modular design. Among these, scholars both domestically and internationally have conducted extensive research on the application of GNSS in collaborative operations (Zhang X. et al., 2025; Hou S. et al., 2022; Chen G. et al., 2024).

The FD20 agricultural robot developed by Denmark's FarmDroid ApS (2024) integrates a centimetre-level positioning system based on RTK-GPS, this system performs precise weeding according to sowing location points with an accuracy margin of error of 5 millimetres. The Bakus multi-functional machine developed by US-based Vitibot (2024) employs GPS positioning to enhance crop yields through mechanical weeding. Willekens A. et al. (2025) proposed a method combining GNSS positioning for label generation with manual correction, providing a technical foundation for automated precision weeding and rapid dataset construction. Kotaniemi J. et al. (2024) developed a weeding robot integrating GNSS navigation with 3D vision, enabling autonomous mechanical weeding operations. Zhang H. (2025) developed a weed-removal machine featuring a GNSS-based inter-vine weeding and obstacle-avoidance control system. Field trials with actual vehicles validated the operational performance of this grapevine inter-row weeder.

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Yang S (2022) devised an adaptive control system for weeders, utilising Hall effect encoders for feedback acquisition. Field tests confirmed its efficacy in substantially reducing the machine's operational resistance during actual work. Fei K. et al. (2024) developed a GNSS-based multi-source information fusion positioning system, with field trials confirming its positioning accuracy approaches that of differential GNSS while significantly reducing hardware costs for precise positioning; Ji P. et al. (2024) developed a weeding robot based on the STM32F405RGT6 controller, employing GNSS positioning technology to ensure operational trajectory accuracy during work; Li J (2025) reported that in complex farmland environments, the fusion of multiple data sources, such as GNSS, encoders, and visual sensors, can effectively improve accuracy and system response time, thereby enhancing operational performance.

Zhao N. (2025) developed a speed closed-loop control system for soybean weeding robots to mitigate performance issues caused by motor speed fluctuations resulting from variations in soil resistance. In mechanical weeding operations, GNSS technology is currently integrated primarily into systems to facilitate practical implementation, providing a foundation for precision field management. However, it exhibits significant measurement errors when applied to low-speed machinery. Furthermore, research on encoders for mechanical weeding in large-scale field operations remains limited. When used for high-speed machinery measurements, encoders are similarly susceptible to substantial errors due to factors such as ground wheel slippage (Paulus S. et al., 2026; Wang Z. et al., 2025; Xing Q. et al., 2022). Therefore, when designing the control system, it is necessary to integrate GNSS and encoder speed measurement data to establish a mathematical model of motor speed, while ensuring real-time responsiveness and reliability under complex field operating conditions.

To address the above issues, a straw-raking control system based on GNSS positioning and encoder fusion speed measurement was designed. This system is intended to achieve speed-adaptive regulation, ensure accurate speed measurement under both high- and low-speed operating conditions, and reduce straw accumulation that could suppress seedling growth. Using a self-developed soybean inter-row weeder as the test platform, a straw-raking control system based on an STM32 microcontroller was constructed. The reliability of the control system was validated through field performance comparison trials.

MATERIALS AND METHODS

System Architecture

The soybean inter-row weeder employs a coordinated operational mechanism comprising a 'straw-raking unit – weeding blade – soil-weed separation wheel'. This system features circumferential serrated straw-raking and collaborative soil-weed separation functions. The straw-raking unit utilises sprocket transmission with motorised drive, supporting independent operation of individual straw-raking modules. Its structure is illustrated in Fig. 1a. To further enhance the operational performance of the soybean inter-row weeder, a control system was developed based on its working principles to optimise the straw-raking unit's efficiency. This system comprises a 'GNSS + encoder' integrated speed measurement module, a human-machine interface module, and an STM32 main control module. The overall design is illustrated in Fig. 1b.

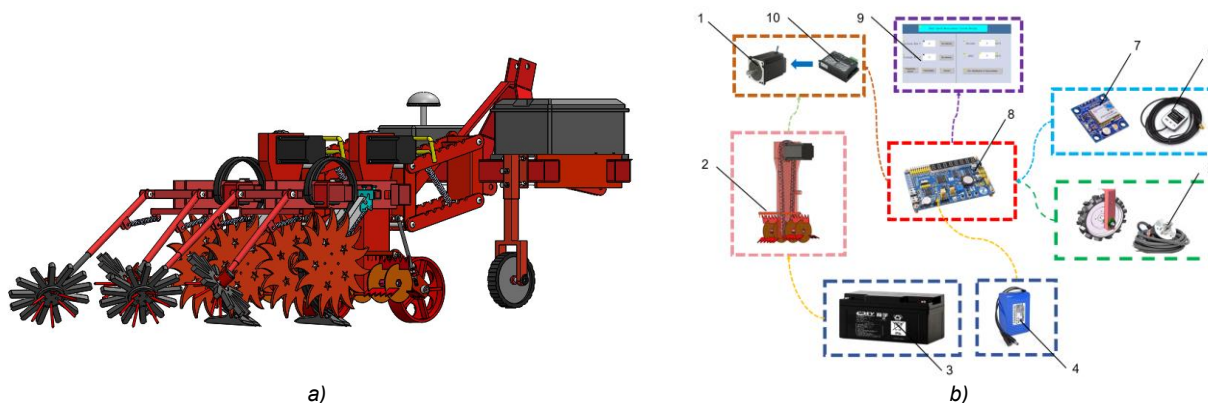


Fig. 1 - Weed Cutter and Straw-Raking Control System

a) Structure of the Soybean Inter-row Weeder; b) Straw-Raking Control System Composition

1- Straw-raking motor; 2- Circumferential serrated straw-raking device; 3- 48V lead-acid battery; 4- 5V lithium battery; 5- Encoder; 6- GNSS antenna; 7- BeiDou signal receiver; 8- STM32 microcontroller; 9- Human-machine interface; 10- Motor driver

Working Principle

During operation, the system sets the straw coverage data per row via human-machine interaction. The straw-raking system reduces trailing distance through pre-emptive operation. GNSS acquires BeiDou positioning data while encoder measure ground wheel speed. Two speed measurement modules obtain the weeder's position and working speed, feeding this data in real-time to the human-machine interface module. The STM32 microcontroller comprehensively processes the acquired data, integrating the 'straw coverage - working speed - straw-raking blade shaft rotation speed' mathematical speed control model. It then outputs PWM pulse signals with specific duty cycles to regulate the straw-raking motor's rotational speed, thereby achieving adaptive adjustment of the motor's speed for the soybean inter-row weeder.

System Hardware Design

The system hardware primarily comprises signal acquisition units, signal processing units, and drive units, as illustrated in Fig. 2. Taking into account both system reliability and future functional expansion, the signal processing unit employs the STM32F411RCT6 as its main control chip. This microcontroller operates at a maximum clock frequency of 100 MHz, features 128k SRAM, and incorporates multiple communication modules, thereby fulfilling the system's control requirements.



Fig. 2 - Control Cabinet Hardware Structure
 1-TJC1060X570 display screen; 2-Terminal block switch; 3-5V power supply; 4-STM32F411RCT6 microcontroller; 5-Cable tray; 6-MSSD-60LMA motor driver

GNSS Signal Acquisition

The ATK1218-BD speed measurement module was selected, whose interface characteristics are compatible with microcontrollers. The serial communication baud rate is set to 115200, with a maximum update frequency of 20 Hz. All key parameters meet the system requirements. To enhance transmission efficiency, the system employs DMA via the serial port to receive and parse the \$GNRMC information, thereby obtaining the current operating speed of the mower, denoted as V_1 . The speed decoding process is illustrated in Fig. 3.

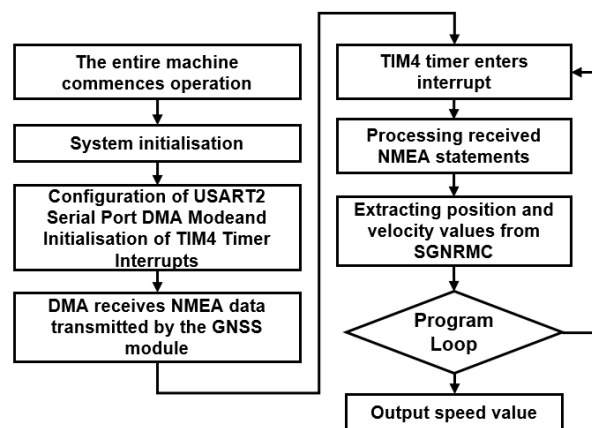


Fig. 3 - Beidou Speed Decoding Process

Encoder Signal Acquisition

The E6B2-CWZ6C incremental encoder was selected to measure rotational speed by counting pulses within the timer interrupt interval. The encoder speed decoding process is illustrated in Fig. 4.

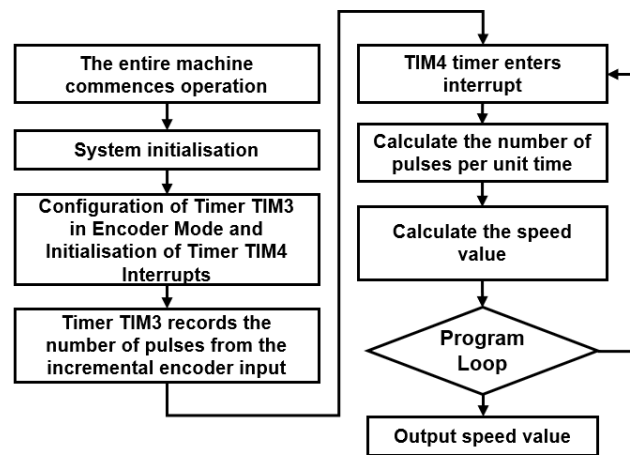


Fig. 4 - Encoder Speed Decoding Process

Specifically, timer TIM3 is configured for Encoder Mode and connected to the encoder's A and B phases respectively; timer TIM4 is set to interrupt every 0.2 seconds. The ground wheel and encoder have a rotational speed ratio of 1:2π. The mower's operational speed is derived from the pulse count obtained by the encoder, as expressed in Equation (1):

$$V_2 = \frac{N_1 D(1 - \delta)}{2N_2 T} \tag{1}$$

where: V_2 is the operating speed of the mower obtained from the encoder, [m/s]; N_1 is the number of encoder pulses within the measurement cycle; D is the ground wheel diameter, which is 0.4 m; N_2 is the number of pulses per revolution of the encoder, which is 1000; T is the measurement cycle, which is 0.2 s; δ is the ground wheel slip rate, ranging from 0.12 to 0.15, which is 0.15 (Zhang S. et al., 2025; Xu, Y.2022).

Design of the Straw-Raking Device Drive Unit

The straw-raking unit's drive assembly primarily comprises a DC brushed motor driver, a DC brushed motor, a sprocket transmission mechanism, and the straw-raking apparatus itself. The sprocket transmission in the soybean inter-row weeder serves to reduce speed and increase torque. The straw-raking motor is the critical component of the drive unit, with its power output meeting operational requirements (Ding L. et al., 2025). During trials using the self-developed soybean inter-row weeder's straw-raking assembly, GNSS and encoder signals were processed by a microcontroller to generate PWM signals with specific duty cycles. This enabled the straw-raking motor's rotational speed to achieve adaptive regulation according to operating conditions, delivering rapid system response and effective performance.

The establishment of the motor speed regulation model fundamentally addresses the operational requirements of the straw-raking device. It must ensure dynamic matching between the forward speed of the implement, the rotational speed of the straw-raking motor, and the straw feed rate. This guarantees consistent straw processing throughout the device's operation. The straw feed rate calculation is shown in Equation (2):

$$Q = V_m L \rho \tag{2}$$

where: Q is the feed rate of straw per unit time, [g/s]; V_m is the working speed of the weeder, [m/s]; L is the working width of the straw-raking device, [m]; ρ is the density of the straw, [g/m²].

The relationship between the motor speed of the weed cutter, the straw feed rate, and the operational performance is shown in Equation (3):

$$n_p = \frac{60V_m L \rho Z_2}{kZ_1} \tag{3}$$

where: n_p is the rotational speed of the motor in the weeder, [r/min]; Z_1 is the number of teeth on the driving gear; Z_2 is the number of teeth on the driven gear; k is the unit time operational performance of the straw-raking device, [g/r].

By outputting a PWM signal via the timer to control the electric motor, the captured value of the compare register exhibits a linear relationship with the motor speed. Combining this with the operating principle of the timer yields Equation (4):

$$V_{CCR} = \frac{n_p V_{ARR}}{n_{\max}} \quad (4)$$

where: V_{CCR} is the value captured in the timer's compare register; V_{ARR} is the value stored in the timer's auto-reload register; n_{\max} is the maximum output rotational speed of the motor when the PWM duty cycle is 100%, [r/min].

Combining Equations (2) to (4), the relationship between the working speed of the mower and the V_{CCR} value in the main controller's timer is expressed as in Equation (5):

$$V_{CCR} = \frac{60V_m L \rho Z_2 V_{ARR}}{k n_{\max} Z_1} \quad (5)$$

Hardware System Circuit Design

The straw-raking motor driver is powered by a 48 V lead-acid battery, and its signal output wires are linked to the microcontroller pins. The motor speed is regulated by adjusting the duty cycle of the PWM signals. A Tao Jingchi X5 serial display serves as the host computer and is powered by 5 V. Its signal output lines are connected to the RX/TX pins. The microcontroller pins provide power to the 'GNSS+encoder' fusion speed measurement module, while the microcontroller itself is powered by a 5 V lithium battery. Signals are transmitted via dedicated UART serial ports to both the host computer and the GNSS component of the fusion speed measurement module. The straw-raking motor control power system is illustrated in Fig. 5.

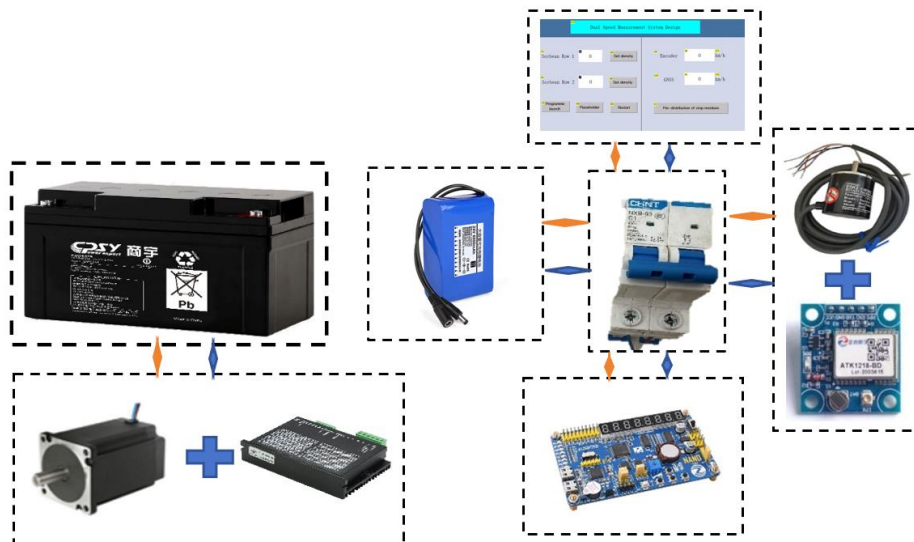


Fig. 5 - Straw-Raking Control Power Supply System Composition

System Software Design

The operational sequence of the soybean inter-row weeder comprises three phases: stationary start-up, acceleration/deceleration transition, and steady-state operation. To accommodate varying speed measurement requirements across these phases and enhance the system's responsiveness to velocity feedback, an electronically controlled system was designed. This system integrates GNSS and encoder fusion for speed measurement and incorporates a preset slip rate compensation mechanism. The speed switching conditions are defined as follows: If the microcontroller receives GNSS speed data V_1 or encoder speed data V_2 , and either value equals or exceeds $4.5 \text{ km} \cdot \text{h}^{-1}$, the operating speed is derived from GNSS speed data V_1 . If both speed values remain below $4.5 \text{ km} \cdot \text{h}^{-1}$, the operating speed is derived from encoder speed data V_2 .

Host Computer Software Design

The system employs a TJC1060X570 serial port display module as the human-machine interface hardware. This module utilises a serial UART interface with an ASCII character string communication protocol, meeting communication requirements in field operation environments.

The primary functions of the straw-raking control system software include setting straw density based on actual field weeding conditions, configuring programme operating modes, and providing real-time feedback on working speed, as illustrated in Fig. 6. Straw density setting serves as the system's initial parameter, dynamically adjusting the reference value for soybean row working speed to optimise straw-raking performance. During operation, the left panel enables normal system functioning, while the right panel provides real-time feedback of GNSS and encoder speed measurements. Human-machine interaction is achieved via the serial port display, which calculates the theoretical motor speed of the current straw-raking device and regulates it by generating a specific frequency PWM signal.

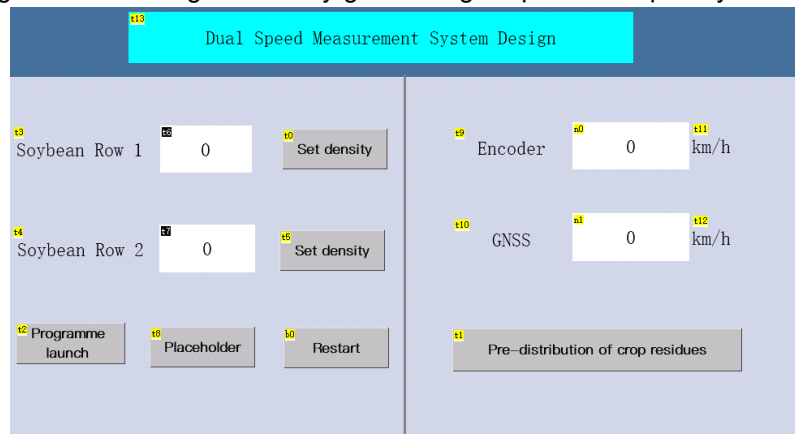


Fig. 6 - Straw-Raking Control System Interface

Lower-level Machine Programme Design

The lower-level machine program was developed based on the STM32F411RCT6 controller, using STM32CubeMX for hardware initialization configuration. Programming and debugging were completed within the Keil µVision v5 environment, with the operational workflow illustrated in Fig. 7.

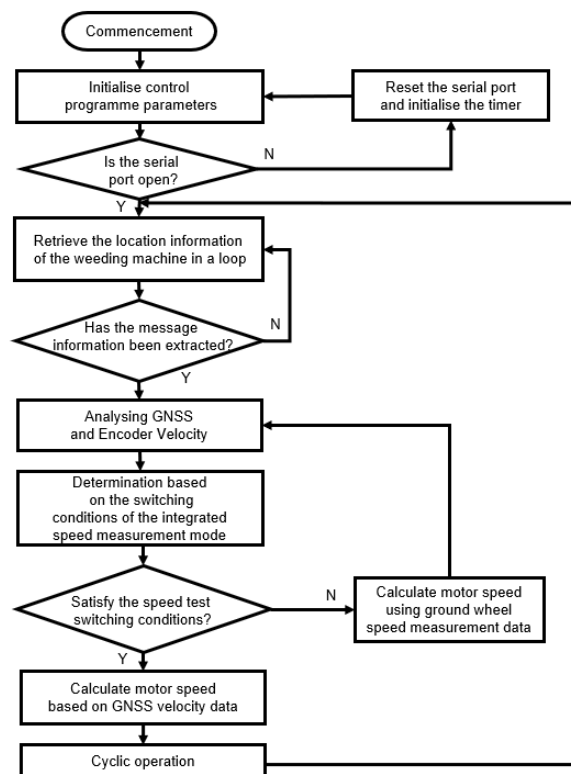


Fig. 7 - Controller Programme Flow

Upon program initialization, the system first receives user-defined soybean row straw density parameters via the serial display. Upon commencing weeding operations, the system enters a real-time control loop: the microcontroller continuously acquires working speed information through a dual-speed measurement system combining GNSS and encoders.

When the working speed is below $4.5 \text{ km}\cdot\text{h}^{-1}$, it uses the encoder's speed measurement data. When the working speed is equal to or exceeds $4.5 \text{ km}\cdot\text{h}^{-1}$, it uses the GNSS speed measurement data. The microcontroller calculates the target motor speed based on preset straw density parameters. Using a mathematical model of the motor speed, it sends corresponding PWM signals to the motor driver, ultimately ensuring that the straw-raking device dynamically adapts its operation to actual working conditions.

Test Conditions and Specifications

To evaluate the operational performance of the straw-raking control system on the weeder, field comparative trials were conducted at the experimental station of the Henan Academy of Agricultural Sciences. Two operational modes were tested: with and without dual-speed control. All other operational parameters remained the same. During the field performance comparison trials, the tractor pulled the soybean inter-row weeder at the prescribed forward speeds. To ensure data reliability and accuracy, the test field was divided into acceleration/deceleration zones and trial zones. Each acceleration/deceleration zone provided a 10 m section for the tractor to stabilize its speed before and after each test run. Each trial zone measured 15 m in length and 1 m in width. Five sampling points, each 1 m long and 40 cm wide, were randomly selected within each row. The numbers of weeds and soybean seedlings, as well as the straw mass, were measured before and after operation in each sampling plot. Three replicate trials were conducted for each working speed, and the results were averaged. This zoning and five-point sampling approach ensured that the weeder maintained the preset working speed, minimized the impact of speed fluctuations on performance, and guaranteed the rigor of the experimental data.

The trial site is representative of a typical Huang-Huai-Hai region winter wheat–summer soybean rotation system, with wheat as the preceding crop. Straw was shredded and incorporated into the soil during mechanical harvesting prior to the field trials. Evaluation metrics were selected in accordance with relevant specifications in the literature, as illustrated in Fig. 8.

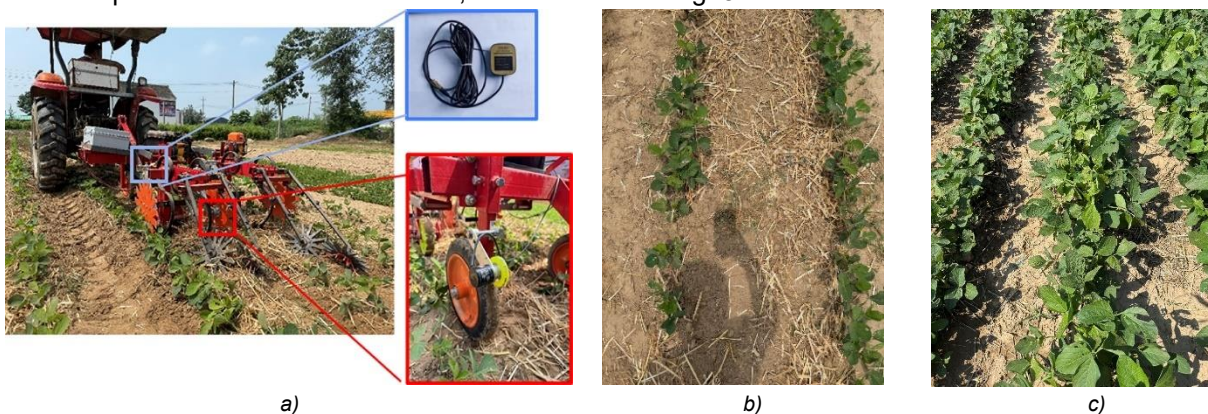


Fig. 8 - Field trial

a) Field performance trials of control systems; b) Assignment outcome; c) Germination status after 10 days of cultivation

The evaluation metrics adhere to the requirements of relevant standards (Diao Z. *et al.*, 2022), as shown in Equations (6) to (8).

$$\psi_1 = \left(1 - \frac{\partial y_1}{\partial y_2}\right) \times 100\% \quad (6)$$

$$\psi_2 = \frac{\partial z_1}{\partial z_2} \times 100\% \quad (7)$$

$$\psi_3 = \frac{\partial m_1}{\partial m_2} \times 100\% \quad (8)$$

where: ψ_1 is the weed control rate, [%]; ∂y_1 is the number of weeds in the monitoring area after the trial, [plant]; ∂y_2 is the number of weeds in the monitoring area before the trial, [plant]; ψ_2 is the seedling injury rate, [%]; ∂z_1 is the number of damaged seedlings in the monitoring area post-trial, [plant]; ∂z_2 is the number of damaged seedlings in the monitoring area pre-trial, [plant]; ψ_3 is the straw coverage rate, [%]; ∂m_1 is the straw mass in the monitoring area post-trial, [g]; ∂m_2 is the straw mass in the monitoring area pre-trial, [g].

RESULTS

The soybean row spacing in the experimental field was 40 cm, with a plant spacing of 15 cm. The straw mulch coverage in the field was 0.71 kg/m². To evaluate system performance across different operating speeds, three velocity gradients were established: 3 km·h⁻¹, 5 km·h⁻¹, and 7 km·h⁻¹. Experiments were repeated three times within the plot to reduce random error, with results presented in Table 1 and Table 2.

Table 1

The control system evaluates the quality results of the machine operation

Operating speed [km·h ⁻¹]	Test number	Number of weeds [plant]	Number of soybean seedling [plant]	Straw quality prior to processing [g]	Weed removal quantity [plant]	Number of damaged seedlings [plant]	Post-operation straw quality [g]	Average weed control rate [%]	Average seedling damage rate [%]	Average straw coverage rate [%]
3	1	12	67	1064	10	2	587			
	2	16	66	896	15	1	453	90.14	1.50	51.66
	3	15	62	997	14	0	491			
5	1	14	66	984	13	2	448			
	2	15	65	1036	14	1	487	93.44	2.05	46.63
	3	17	63	1147	16	1	543			
7	1	16	64	1163	15	3	503			
	2	13	67	1098	12	2	461	95.35	3.10	41.89
	3	10	62	1276	10	1	516			

Table 2

No control system to evaluate the quality of machine operation results

Operating speed [km·h ⁻¹]	Test number	Number of weeds [plant]	Number of soybean seedling [plant]	Straw quality prior to processing [g]	Weed removal quantity [plant]	Number of damaged seedlings [plant]	Post-operation straw quality [g]	Average weed control rate [%]	Average seedling damage rate [%]	Average straw coverage rate [%]
3	1	14	63	1056	12	2	567			
	2	16	64	1173	14	2	532	86.63	2.62	49.84
	3	15	64	941	13	1	475			
5	1	14	66	943	13	2	423			
	2	12	64	1033	11	3	408	90.40	4.09	42.68
	3	15	66	879	13	3	384			
7	1	15	62	992	14	4	335			
	2	14	64	1087	13	3	433	92.83	5.38	36.94
	3	13	60	1153	12	3	429			

As shown in Tables 1 and 2, with increasing operating speed, the weed removal rate, seedling damage rate, and straw coverage rate of the soybean inter-row weeder exhibited varying degrees of change in the control trials with and without the control system. As the operating speed increased, both the weed removal rate and seedling damage rate showed a continuous upward trend, while the straw coverage rate showed a decreasing trend. At different operating speeds, the average weed removal rate was 92.98% and 89.95%, respectively, the average seedling damage rate was 2.22% and 4.03%, respectively, and the average straw coverage rate was 46.73% and 43.15%, respectively. The test results indicate that the overall machine performance with the control system is superior. By analysing the mean and standard deviation of each evaluation indicator, the impact of the control system on the overall operational performance of the soybean inter-row weeder is assessed, as illustrated in Fig. 9.

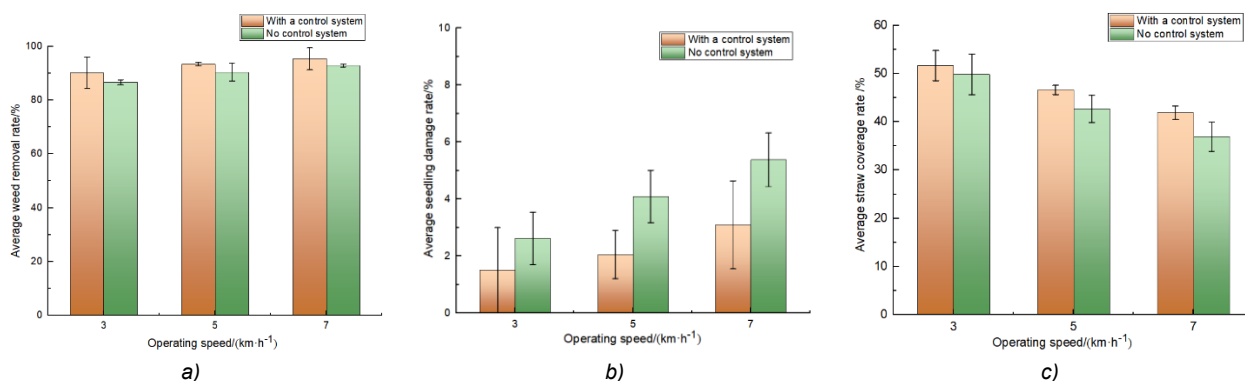


Fig. 9 - The impact of different speed tiers on each evaluation indicator

Trends with respect to operating speed are illustrated in Fig. 9. These results indicate that the application of the straw-raking control system improves the overall operational performance of the machine. Across the three operating speeds, the maximum differences in average weed removal rate, average seedling damage rate, and average straw coverage rate compared with the system without straw-raking control were 3.51%, 2.28%, and 4.95%, respectively. However, no clear trends were observed in the mean values and standard deviations. This is attributed to variations in field conditions. With autonomous adaptive regulation of the straw-raking device's rotational speed, straw accumulation and seedling burial caused by mismatched feed rates and forward speed are avoided. This prevents straw from accumulating in the seedling zone due to interference with the weeding blades during operation, while simultaneously establishing a low-straw interference zone that enables effective weeding.

CONCLUSIONS

To enhance the operational performance of soybean inter-row weeders, a straw-raking control system was designed based on dual-speed measurement using GNSS positioning and encoder. Utilizing an STM32 microcontroller as the main controller, this system established dual-speed measurement mode rules and a straw-raking control unit. A dedicated control interface was developed for the system. The specific research accomplishments are as follows:

A straw-raking control system for soybean inter-row weeders was developed, incorporating a speed measurement model based on GNSS and encoder fusion. A corresponding software interface was created, and the system used an STM32 microcontroller as the main controller. A mathematical model linking straw coverage rate, operating speed, and straw-removal blade shaft rotational speed was established, which defined the integrated speed measurement rules for the straw-raking device. This further enhanced the performance of the self-developed weeder and improved weeding operation quality. The study focused on evaluating the impact of the straw-raking control system on the soybean inter-row weeder's performance. Field performance comparison trials were conducted at three working speeds (3, 5, and 7 km·h⁻¹), with and without the straw-raking control system as experimental controls. The results showed that at 7 km·h⁻¹, the average weed removal rate, seedling damage rate, and straw coverage rate were 95.35%, 3.10%, and 41.89%, respectively. Compared to the system without straw-raking control, these values represented increases of 2.52% and 4.95% in the average weed removal rate and straw coverage rate, respectively, while the average seedling damage rate decreased by 2.28%. These results met the agronomic requirements for soybean inter-row weeder operations.

Given the challenges encountered in complex mechanized agricultural operations, such as soybean seedling-stage straw mulching, future research should focus on two key areas. First, the development of closed-loop control systems is essential. Current systems predominantly rely on open-loop control due to limitations in design experience and manufacturing constraints, which makes it difficult to accurately monitor motor operating states and straw movement behavior. Greater integration of intelligent control technologies and real-time feedback mechanisms—such as machine vision and deep learning—will be necessary to address these limitations. Second, system robustness should be enhanced through extensive field trials conducted under diverse and complex environmental conditions to comprehensively validate overall machine performance. These efforts will ultimately improve the operational efficiency and adaptability of soybean inter-row weeders across a wide range of field conditions.

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